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Research paper

Morphometric and Morpho-Tectonic Screening and Prioritisation of Sub-Basins in The Kabini River Basin, Kerala: Remote Sensing and GIS-Based Approach

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Abstract

The present study reports the morphometric and morpho-tectonic analysis of six sub-basins (WS-1 to WS-6) of the Kabini River basin, Wayanad, Kerala, by considering different linear, areal and relief parameters (Drainage density, Stream frequency, Drainage texture, Bifurcation ratio, Circularity ratio, Elongation ratio, Shape factor, Total Relief, Relief ratio and Ruggedness number) derived from CartoDEM data. An equal-weight compound ranking scheme was used to rank the sub-basins to give a repeatable ranking. Three robustness checks were performed by leaving one parameter out, leaving out relief and 10,000-run random weighting. The WS-3 and WS-5 consistently ranked first (WS-3 ranked first in 86% of cases), whereas the WS-2 and WS-4 ranked in medium priority and WS-1 and WS-6 ranked in low priority. Basin-level morpho-tectonic indices (Transverse topographic symmetry factor, Hypsometric integral and Asymmetry factor) are given for reference and are not diagnostic. The results indicate that the trunk stream shows moderate asymmetry from TTSF. The asymmetry factor suggests it is nearly symmetric (50.52%). The low value of the hypsometric integral indicates it is at a late erosional stage. The Stream Length Gradient Index was inconsistent and so omitted. This study does not allow any separation between lithological, climatic and erosional effects and tectonic effects, as the indices are derived from DEM data; however, the ranking can be used as a screening tool to identify sub-basins for structural, geophysical and field analysis.

Keywords: *Morphometric Analysis; Neo-Tectonics; Asymmetry Factor; Transverse Topographic Symmetry Factor; Hypsometric Integral; Kabini River Basin.*

1. Introduction

River basin and its sub-basin analysis and prioritisation studies have gained much importance over time, particularly in a watershed framework (Parsia, 2023). Morphometric determinants are some of the basic attributes used to understand the geomorphological, hydrological, and groundwater characteristics of a region (Choudhari et al., 2018). Kabini River Basin is a major hydrologic entity located in the Western Ghats region of Kerala. It is necessary to carry out a meticulous morphometric analysis using remotely sensed data and GIS techniques to understand the basin's nature and characteristics. Several works of literature reveal that remote sensing and GIS techniques help extract and analyse basin properties (Das et al., 2021). Horton (1945) and Strahler (1964) have put forth various quantitative measures used extensively for drainage basin analysis. Morphometric analysis refers to the study of the shape of the earth's surface and the mathematical relationship between its components (Miller, 1953).

The morphometric parameters can be broadly classified into three groups, namely linear, areal, and relief (Meshram & Sharma, 2017). Stream order, stream length, bifurcation ratio, and drainage density are a few parameters that fall under the category of linear measurements. Basin area, perimeter, form factor, and circularity ratio are a few areal parameters. They are primarily used to identify the basin's hydrological response characteristics, for instance, runoff, peak discharge, and infiltration (Patil & Bhagwat, 2023). Morphometric analysis using remotely sensed data has become widespread in hydrological studies, particularly in watershed studies, as the last two decades have seen exponential improvements in remote sensing data processing capabilities (Javed et al., 2011). The availability of high-resolution digital elevation data from spaceborne sensors has enabled automated extraction of drainage networks, thus improving the accuracy of morphometric calculations (O'Callaghan & Mark, 1984). Remote sensing data and satellite imagery, therefore, play a crucial role in understanding hydro-geomorphological characteristics of a basin (Aher et al., 2014).

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There have been several studies addressing the prioritisation of the sub-watersheds based on their soil and water conservation aspects using morphometric analysis (Verma et al., 2022). This work demonstrated that integration of land use/land cover information with morphometric data helps identify sub-watersheds requiring conservation attention. In another work, a quantitative morphometric model was used for prioritisation of 10 sub-watersheds of the semi-arid Pennar basin, Bapatla district, Andhra Pradesh. The prioritisation was based on CartoDEM-derived drainage area, perimeter, form factor, shape factor, and sinuosity, along with land use/land cover, slope, soil, and rainfall data. The authors identified the sub-watersheds with higher drainage density, higher ruggedness numbers, agricultural dominance, and sandy loam soil as the most vulnerable and prioritised them based on their conservation needs (Naik et al., 2026).

Priority is generally given to the sub-watersheds based on the value of parameters calculated. For instance, in a basin, a study was carried out to prioritise its sub-basins based on the weightage assigned to selected hydro-morphometric parameters. The weightage was calculated based on their impact on the basin's hydrological response. Further, the parameter values were used to prioritise the sub-basins according to their conservation needs, with special focus on soil conservation (Sharma et al., 2023). Similar GIS-based morphometric analysis has been carried out to assess the status of sub-basins and prioritise them based on their conservation and development potentials, particularly in semi-arid (Gajbhiye et al., 2014) and evergreen-vegetation regions.

The Kabini River basin is part of the larger Cauvery River basin that stretches across Kerala, Tamil Nadu, and Karnataka. The river flows through Kerala and drains into Karnataka, joining the Cauvery River in Karnataka. The land slopes gently to the east and becomes steeper to the west (Fig. 1). The study area is characterised by a tropical monsoon climate, wherein the rainfall varies significantly both spatially and temporally. This variability governs the spatial variation in the infiltration, runoff, and overall hydrological response of the basin. As part of the Western Ghats 'World Heritage Biosphere Reserve,' the study area is home to a great number of species that are vulnerable to climate change and other anthropogenic activities.

The advancements in remote sensing and GIS data and their applications continue to create new opportunities for exploring and prioritising the critical sub-watersheds. Some works of literature adopt a Principal Component Analysis (PCA), Weighted Sum (WS) approach, or a hybrid approach such as multi-criteria clustering or multi-attribute decision-making while carrying out prioritisation (Gururani et al., 2024; Regmi et al., 2023).

While morphometric analysis of the basin is a well-established domain, the role of tectonic forces on the physiographic attributes of the basin is not well established. Particularly the tectonic influence on the hydrological regime in the Western Ghats region, located in the stable portion of the Indian plate-exhibiting lineament controlled drainage patterns and low to moderate intraplate seismicity needs to be investigated. Tectonic and structural controls can play an important role in influencing the hydrological regime of the basin. Understanding the influence of tectonic controls on the physiography and morphology helps in better understanding the hydrological system, keeping in mind the influence of non-tectonic factors.

The present work involves morphometric and morpho-tectonic analysis of the Kabini River basin. The specific objectives of the work were to: (i) derive and calculate linear, areal and relief morphometric parameters using RS and GIS techniques; (ii) assess the possible tectonic signature on the basin using various tectonic geomorphic indices at basin scale (TTSF, hypsometric integral and asymmetry factor) and interpretation of geological and geomorphological context; and (iii) prioritise the sub-basins based on a repeatable ranking method involving sensitivity analysis. The mapping of lineament density and stream length gradient index could not be conducted reliably. These were thus not used for prioritisation. Land use land cover data have been used only to understand the context.

2. Study area

The Kabini River basin is located in Wayanad district of Kerala and is a major tributary of the Cauvery River. Extending between approximately 11°36′18″N and 12°15′N Latitude and 76°04′E and 76°54′E Longitude, the basin covers the entire area of the Wayanad plateau and extends into Karnataka, with the river originating near 11°48′01″N, 76°04′29″E in the Wayanad district (Fig. 1).

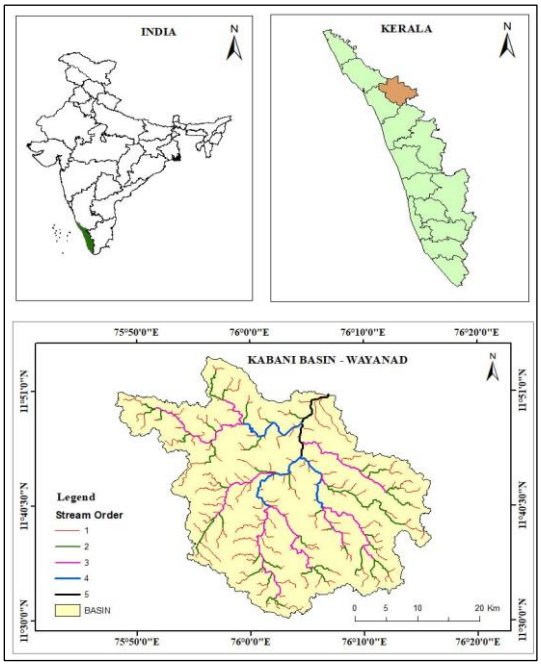


Fig. 1: Location Map of the Study Area.

The basin consists of a variety of terrain features such as dunes and reserve forests, floodplains along the river, highly and less dissected areas, piedmont transition zones, quarries, mining sites, and watercourse observatories. The drainage patterns are well-developed, ranging from order-1 headwater streams to higher-order streams as the main trunk streams. The heavy monsoon rain that falls in the basin, mainly from the southwest monsoon, makes it all the more important to carry out watershed management and conservation practices.

The Kabini basin's Wayanad Plateau is underlain by granite-gneiss-charnockite-migmatite complexes of hard rock formations. The fractures and lineaments that develop in these rocks act as passages for groundwater, while narrow alluvial and valley-fill deposits occur along the rivers. Groundwater occurs as phreatic water in weathered mantle and fractured rocks. The basin's soils are predominantly brown hydromorphic and alluvial deposits, which vary in their drainage, depth, and texture. The soils in the valleys are deep and poorly drained and are loamy, while those on the hillslopes are well drained and range between clayey and gravelly. The rich alluvial deposits in the valleys enable the farmers to grow a variety of crops like spices, plantains, and paddy. The Kabini Basin is underlain by hard crystalline rocks such as granite, gneiss, charnockite, and migmatite, which form the bedrock of the Wayanad Plateau. The soils are broadly classified as brown hydromorphic and alluvial, varying in drainage, depth, and texture. Valley areas have deep, poorly drained loamy soils, while hill slopes feature well-drained, clayey or gravelly soils. These fertile soils support diverse crops like spices, plantain, and paddy.

3. Data & Methodology

The study determines and prioritises the sub-basins of the Kabini River based on their morphometric characteristics using remote sensing and GIS techniques by considering linear, areal, and relief parameters based on Horton's (1945) and Strahler's (1964) approach.

3.1. Data

Table 1: Data Used in Analysis

SI. No.	Data	Parameter	Source
1	CartoDEM (Cartosat-1, 30 m)	Drainage Map Slope Map	Indian National DEM (NRSC/ISRO, Bhuvan)
2	Sentinel-2A	LULC	ESA Copernicus (2025)
3	Soil	Soil Map	https://commons.wikimedia.org/wiki/File:Kerala_soil_map_NBSS.png
4	Geology	Geology Map	https://geodataindia.gov.in/login
5	Geomorphology	Geomorphology Map	https://geodataindia.gov.in/login

3.2. Methodology

While following the work of Joji et al. (2013) and Vandana (2013) for the Kabini basin and other rivers of Kerala state, the linear parameters were calculated as stream order (u), stream number (Nu), stream length (Lu), mean stream length (Lsm), stream length ratio (Lur), bifurcation ratio (Rb), length of overland flow (Lo), and basin length (Lb). The areal parameters of the basin area (A), basin perimeter (P), form factor (Rf), shape factor (Sf), elongation ratio (Re), circularity ratio (Rc), drainage texture (Dt), stream frequency (Fs), and drainage density (Dd) were estimated using the methodology of Anish et al. (2021) adopted for the analysis of different river basins in Kerala state. The relief parameters that have been taken into consideration are the height of the basin mouth (H), maximum height (Z), total basin relief (R), relief ratio (Rh), ruggedness number (Rn), and basin ruggedness index (Bri). These parameters were evaluated using a digital elevation model according to Aju et al. (2022), applied to tropical river basins of the Southern Granulite Terrain for investigating their physiography. Tectonic aspects were analysed, following Aju et al. (2022), through the calculation of stream length-gradient index (SL), transverse topographic symmetry factor (TTSF), hypsometric curves, and asymmetry factor (AF) for the six Kabini River Basin sub-basins.

Data processing workflow: CartoDEM tile data was mosaicked across the basin and projected into WGS 84 / sink filling and D8 flow direction were hydrologically conditioned into UTM Zone 43N. The DEM and flow accumulation grids were created in ArcGIS 10.5. The DEM had a 30m resolution. Stream extraction was performed using a flow accumulation threshold to create an ordered stream network following the method of Strahler (1952). The threshold value controls the absolute drainage density within the basin; this value was identical for all sub-basins. The outlet locations were defined as confluence points where fourth- and higher-order streams meet. The six sub-basins (WS-1 to WS-6) were automatically defined using the flow direction grid. Basin area, perimeter and length were calculated from the resulting polygons. Lineaments were not extracted. All values were calculated using the formulae listed in Table 2. The parameters were prioritised using the compound ranking method described in Section 3.3.

Table 2: Morphometric and Tectonic Parameters, Formulae and References

Sl. No.	Variable	Formula	Reference
	A. Linear parameters		
1	Stream order (u)	Hierarchical rank	Strahler (1952)
2	Stream number (Nu)	Total number of streams of order u	Horton (1945)
3	Stream length (Lu), km	Total stream length of order u	Strahler (1952)
4	Mean stream length (Lsm)	Lu / Nu	Strahler (1952)
5	Stream length ratio (Lur)	Lu / Lu-1	Strahler (1952)
6	Bifurcation ratio (Rb; ΣRb = sum of order-wise ratios)	Nu / Nu+1	Strahler (1952)
7	Length of overland flow (Lo), km	1 / (2 * Dd)	Horton (1945)
8	Basin length (Lb), km	GIS software analysis	Schumm (1956)
	B. Areal parameters		
9	Basin area (A), km²	GIS software analysis	Schumm (1956)
10	Basin perimeter (P), km	GIS software analysis	Schumm (1956)
11	Form factor (Rf)	A / Lb²	Horton (1932)
12	Shape factor (Sf)	Lb² / A	Horton (1932)
13	Elongation ratio (Re)	1.128 * √A / Lb	Schumm (1956)
14	Circularity ratio (Rc)	4πA / P²	Miller (1953)
15	Drainage texture (Dt)	Nu / P	Smith (1950)
16	Stream frequency (Fs)	Nu / A	Horton (1932)
17	Drainage density (Dd), km/km²	Lu / A	Horton (1932)
	C. Relief parameters		
18	Height of basin mouth (H), m	GIS analysis/DEM	—
19	Maximum height of the basin (Z), m	GIS analysis/DEM	—
20	Total basin relief (R), m	R = Z − H	Strahler (1952)
21	Relief ratio (Rh)	R / Lb	Schumm (1956)
22	Ruggedness number (Rn)	Dd × R / 1000 (R in m)	Chorley (1972)
23	Basin ruggedness index (Bri)	Dd * (H/1000)	Chorley (1972)
	D. Tectonic Parameters		
24	Stream length-gradient index (SL)	(ΔH / ΔL) × L; L = channel length from the segment midpoint to the source (not used; see section 4.7)	Hack (1973)
25	Transverse topographic symmetry factor (TTSF)	Da / Dd (0–1); Da = distance from the basin midline to the active meander belt, Dd = distance from the midline to the basin divide	Cox (1994)

26	Hypsometric curve and integral (HI)	HI = (Hmean − Hmin) / (Hmax − Hmin)	Strahler (1952); Pike & Wilson (1971)
27	Asymmetry factor (AF)	100 × (Ar / At); Ar = basin area to the right of the trunk stream (downstream view), At = total basin area	Hare & Gardner (1985)

The SL index was calculated initially to assess the influence of uplift and lithology on stream networks (Aju et al., 2022). However, the results were found to be unreliable (section 4.7), so the index was not used in interpretation. The TTSF was used to assess the transverse displacement of the main stream from the basin centerline across nine transects (Cox, 1994). This provides a measure of the overall asymmetry of the basin shape. Basin asymmetry can be caused by tilting, but can also be affected by lithology and drainage development. To provide an overall measure of the asymmetry of the basin, the asymmetry factor was calculated (Hare & Gardner, 1985; Aju et al., 2022). Hypsometric curves were plotted using the area-height distribution technique. This allowed assessment of the erosional (geomorphic) stage of the basin. If the HI was >0.6, then the basin was considered youthful; if between 0.35-0.6, it was considered mature; and if <0.35, then old (Strahler, 1952). Analysis of the hypsometric integral alongside morpho-tectonics has been used to assess the potential effect of neo-tectonic activity on river basins in southern India (Ramkumar et al., 2019). Morpho-tectonic analysis was undertaken to prioritise the sub-basins within the study based on the strength of morphometric indicators that may be indicative of structural/tectonic influence. This is explained in Section 3.3.

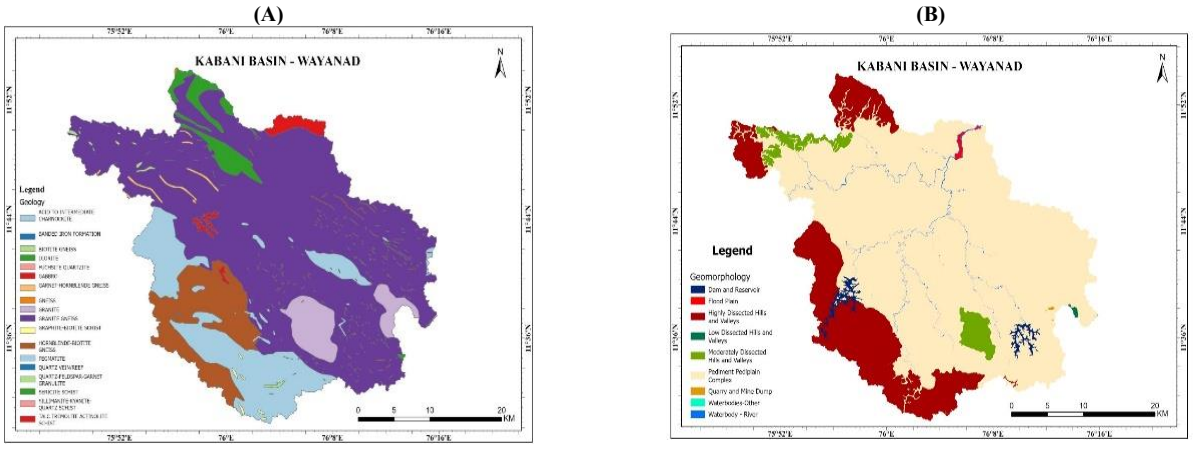
Differentiating tectonic from non-tectonic influence: Morphometric parameters can be influenced by a range of factors including lithology, rainfall and erosional history. As such, the following criteria were used. (i) The geology and geomorphology maps (Figure 2a,b) were compared to the sub-basin pattern to identify if the highest-ranking sub-basins coincide with different lithologies or landforms. (ii) There is a clear trend from west to east of increasing relief and rainfall, which can also affect the drainage density, texture, and relief. (iii) If there were more than one independent index pointing towards a tectonic interpretation, then this would be accepted as a hypothesis. (iv) No independent structural, seismic, geodetic or field data were available for this study, so any tectonic statements are shown as hypotheses.

3.3. Compound-ranking prioritisation

Ten parameters were utilised: drainage density (Dd), stream frequency (Fs), drainage texture (Dt), total bifurcation ratio (ΣRb), circularity ratio (Rc), elongation ratio (Re), shape factor (Sf), total relief (R), relief ratio (Rh) and ruggedness number (Rn). Mathematical functions were removed to prevent duplication; these included: (Lo = 1 / 2Dd, Rf = 1/Sf, Re = 1.128√Rf). Additionally, area-related parameters were not used (Nu, Lu). For each sub-basin, an overall rating was calculated. Sub-basins with the highest drainage density, stream frequency, drainage texture, total bifurcation ratio, shape factor, total relief, relief ratio and ruggedness number were given a rating of 1 (indicating high levels of dissection, fracturing, and relief). Sub-basins with the lowest circularity ratio and elongation ratio were given a rating of 1 (indicating more elongate basins). If two sub-basins had the same value, they would receive the lower rating (Vandana 2013, Aju et al. 2023). An overall value was calculated using: CV = Σ. Sub-basins with the lowest CV value were prioritised. All parameters were given the same weighting in the base case (wi = 1). This was because no independent evidence could be found to suggest that parameters should have different weighting. Weights were not applied within the GIS software. To test robustness, parameters were removed one at a time (a), the whole relief group was removed (this also includes the unverified value of relief in WS-6) (b), and 10,000 random weight vectors from a flat Dirichlet distribution were produced, and the frequency of sub-basins receiving each rating was recorded (c). Tectonic indices (TTSF, HI and AF) were not used in the calculation of the overall value as they were calculated using basin values. SL was not reliable. Dd, Rb and relief can be caused by non-tectonic factors, meaning that CV is a morphometric screening index.

4. Results and Discussion

4.1. Basic information of the study area



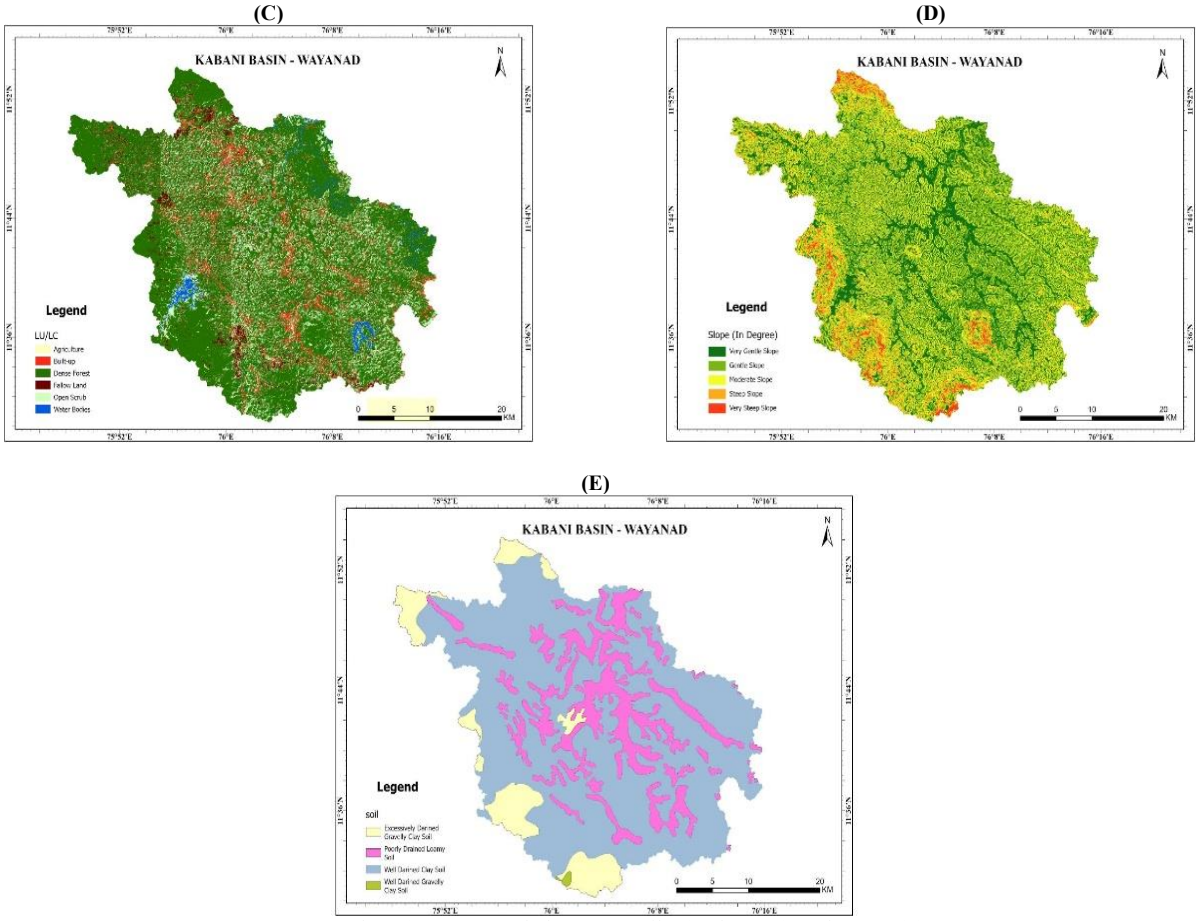


Fig. 2: Geology (A), Geomorphology (B), Soil (C), Slope (D), and LULC (E).

4.1.1. Geology

The rock formations (Figure No: 2. 2a) in the Kabini basin, Wayanad, possess a wide range of rock types, as seen in the geological map. The distribution of gneissic and metamorphic rocks (in purple) was dominant in most parts of the basin, while charnockite and crystalline rocks were found to be widespread in the central and eastern parts of the basin. On the contrary, granite and other rock formations were scattered all over the basin. The green and light blue colours indicated the presence of rocks in the northern and northwestern parts for the most part, while the brown and light blue colours were common in the southern region. The underlying geology greatly influences the river, soil type, location of settlements and vegetation in the region.

4.1.2. Geomorphology

As seen in the geomorphology map (Figure No: 2. 2 b), the Kabini basin presents several landforms including denudational hills, plateaus, lateritic ranges, valleys, plains and depressions, among others. The denudational hills were the most common landform and widespread in the northern and western parts of the basin, occurring sparsely in the southern region. In contrast, plateaus and lateritic ranges were widespread in the western and southern parts of the basin, while valleys, plains and depressions were common in the central part of the basin. Further, the network of streams and rivers in the region is a controlling factor for the occurrence of large floodplains in the Kabini basin. Together with the influence of the landforms on the location and pattern of the river system, the geomorphological features have a significant influence on the hydrological regime as well as the areal distribution and pattern of different vegetation communities.

4.1.3. Soil

As indicated by the soil map (Figure No: 2. 2c), the Kabini basin comprises different soil types, including well-drained clayey soils (blue), which were the dominant parent material, rocky and mixed loamy soils (pink), peripheral and southern deep well-drained clayey soils, and small pockets of well-drained loamy soils in the region. The soil types found in the Kabini basin vary significantly with slope, drainage, parent material and geomorphology, as seen in the figure below. However, the well-drained clayey soils were dominant, followed by the rocky-loamy soils as parent materials.

4.1.4. Slope

As demonstrated by the Slope Map (Figure No: 2. 2d) below, the slopes in the Kabini basin vary from gentle (1%), very gentle (less than 1%), steep (81%), and very steep (more than 81%). The gentle and very gentle slopes were widespread in the central, northern and eastern parts of the basin, while moderate slopes were dominant in the western and southern parts of the basin and its periphery. Further, the southern and western parts of the basin's periphery also possessed steep and very steep slopes, typical of mountainous regions. Generally, the central part of the basin had gentle slopes characteristic of foothills, while the periphery possessed steep slopes typical of mountainous landscapes. As such, the steepest slopes in the Kabini basin are located in the southern and western parts of the basin's periphery and are highly likely to experience greater erosion and expose nearby human lives and property to damage and destruction.

4.1.5. Land use/land cover (LULC)

According to the land use/land cover map (Figure No. 2. e), forests and agriculture covered most of the Kabini basin, with forest cover being widespread in the western, southern, and northern fringes of the basin, while agriculture was widespread in the central and eastern parts of the basin and was ideal for food crop production. The pattern suggests that most settlements in the Kabini basin were found in the agricultural land use type in the central and eastern parts of the basin. In addition, isolated patches of open scrub and water bodies were found in the central and southern parts of the basin. Overall, the land use/land cover of the Kabini basin consisted of a mix of natural vegetation (forests) and human-influenced land cover types, with settlements found predominantly in the proximity of human habitations, with the exception of some isolated locations that lacked direct access to a road.

4.1.6. Implication for interpretation

The main lithology in the basin is gneiss-charnockite-migmatite (Fig. 2a), meaning there are few primary lithological differences between sub-basins. However, differences in the number of joints, depth of weathering and amount of laterite coverage are not shown on the geological map (Fig. 2b). This also affects the drainage density and relief. There is a large difference in relief between the east and west of the basin. This can mean some of the morphometric differences between sub-basins have been caused by differences in climate/erosion. These are not quantified here, and so the morphometric features below can only be assumed to be evidence of possible structural/tectonic controls.

4.2. Linear morphometric parameters

The basin shape and linear parameters of the six sub-basins (WS-1 to WS-6) are shown in Tables 3 and 4. The sub-basin areas range from ~112 km 2 (WS-4) to ~335 km 2 (WS-3). The total area of the six sub-basins is ~1198 km 2. All sub-basins have a normal Horton type decreasing pattern of the number of streams with increasing order. First-order streams are more dominant. This is typical of a mature dendritic drainage network in hard rock terrain but does not indicate any tectonic rejuvenation. The sub-basin with the maximum number of streams and total stream length is WS-3 (69 streams, 192.38 km). The sub-basin with the least number of streams and total stream length is WS-4 (19 streams, 58.65 km). However, these values are proportional to the area of the basin and therefore have not been used in the ranking process. The sub-basins WS-1, WS-4 and WS-5 have a high mean length for third-order streams (20.04, 19.75 and 19.80 km respectively). WS-5 also has a high mean length for fourth-order streams (15.33 km). These values may indicate structurally controlled valleys but may also be due to the low number of higher-order segments. These values are therefore considered to be indicative.

Table 3: Basin Geometry Inputs

Sub-basin	Area, A (km²)	Perimeter, P (km)	Basin length, Lb (km)
WS-1	157.6	84.2	20.9
WS-2	133.3	60.0	20.7
WS-3	335.0	140.8	37.4
WS-4	112.4	63.3	23.7
WS-5	305.8	85.1	27.7
WS-6	154.2	67.4	23.5
Total	1198.4		

Drainage density (Dd = Lu/A) was calculated using the updated stream lengths and areas, and ranged from 0.51 km/km 2 (WS-1) to 0.63 km/km 2 (WS-6), with WS-5 (0.58) and WS-3 (0.57) also showing high values. As this is a low value in absolute terms, drainage density can only be interpreted relatively. Errors were made in the previous versions of the linear and areal tables, so drainage density values have been changed from 1.17 to 1.23. This has affected the overland flow length (Lo = 1/2Dd) and ruggedness number. Cumulative stream length ratio (SLR) showed large variation, with WS-3 having the highest values at 1.83, followed by WS-2 (1.44). The individual ratios range from 0.17 (III/II, WS-2) to 1.0 (V/IV, WS-3). The bifurcation ratio sum (ΣRb) ranged from 7.50 (WS-4) to 12.48 (WS-3). WS-6 (6.5) and WS-3 (4.73) had high I/II ratios. Values greater than about 5 are often associated with tectonic control or elongate basins. However, they can also be associated with steep relief and homogeneous lithology, so they are only indicative. Drainage texture (Dt = Nu/P) ranged from 0.30 (WS-4) to 0.74 (WS-5). WS-5 and WS-2 (0.50) had the highest drainage textures. Overland flow length ranged from 0.79km (WS-6) to 0.98km (WS-1). The lowest values were WS-6 and WS-5, meaning surface runoff will reach the channels fastest.

Table 4: Linear Morphometric Parameters and Linear-Group Rank

Sub-Basin	Stream Number	Stream Length (km)	Mean Stream Length (3rd Order) (km)	Dd (km/km²)	ΣSLR	ΣRb	Dt	Lo (km)	Linear-group rank
WS-1	32	80.67	20.04	0.51	0.41	10.17	0.38	0.98	5th
WS-2	30	71.65	7.33	0.54	1.44	10.67	0.50	0.93	3rd
WS-3	69	192.38	7.56	0.57	1.83	12.48	0.49	0.87	2nd
WS-4	19	58.65	19.75	0.52	0.54	7.50	0.30	0.96	6th
WS-5	63	178.65	19.80	0.58	0.91	11.95	0.74	0.86	1st
WS-6	31	97.74	15.31	0.63	0.40	10.50	0.46	0.79	4th

4.3. Areal morphometric parameters

The areal parameters (Table 5) show that the Rc values range from 0.21 (WS-3) to 0.53 (WS-5), Re values range from 0.51 (WS-4) to 0.71 (WS-5), FF values range from 0.20 (WS-4) to 0.40 (WS-5), and SF values range from 2.50 (WS-5) to 4.97 (WS-4). The lowest Rc, Re and FF values combined with the highest SF values indicate that the most elongated sub-basins are WS-3 and WS-4, while the most compact sub-basins are WS-5 and WS-1. This elongation of the basins could be due to tectonic controls, as the drainage patterns are influenced by the presence of structural features such as faults, shear zones and dykes. However, this can also be influenced by the nature of the source rocks, the location of the divides, and the rules used for delineation.

The drainage texture (Dt) values range from 0.30 (WS-4) to 0.74 (WS-5). The high value in WS-5 indicates a high drainage texture, which may be caused by fracturing, low permeability in the hard rock substrate, or high rainfall. The stream frequency values range from a low value of 0.169 (WS-4) to a high value of 0.225 (WS-2). The highest values are found in WS-2 (0.225), WS-3 (0.206) and WS-5 (0.206). The re-calculated drainage densities (0.51 – 0.63km/km 2) are highest in WS-6 (0.63), WS-5 (0.58) and WS-3 (0.57). High Dd, Fs and Dt

values indicate a more dissected landscape; however, these values are influenced by many factors including rainfall, vegetation, lithology and permeability. These controls cannot be distinguished from these data.

Table 5: Areal Morphometric Parameters and Shape-Group Rank

Sub-Basin	Rc	Re	FF	SF	Dt	Fs	Dd (km/km²)	Shape-group rank
WS-1	0.28	0.67	0.36	2.80	0.38	0.203	0.51	4th
WS-2	0.47	0.63	0.31	3.22	0.50	0.225	0.54	5th
WS-3	0.21	0.55	0.24	4.15	0.49	0.206	0.57	1st (tied)
WS-4	0.36	0.51	0.20	4.97	0.30	0.169	0.52	1st (tied)
WS-5	0.53	0.71	0.40	2.50	0.74	0.206	0.58	6th
WS-6	0.42	0.60	0.28	3.51	0.46	0.201	0.63	3rd

4.4. Relief morphometric parameters

The relief parameters (Table 6) show the largest variation between sub-basins. The total basin relief (R) ranges from 273.59m (WS-2) to 1763.62m (WS-5) for the sub-basins with plausible values, with the next highest value being 1589.37m (WS-3). The value of 1.00m (WS-6) is physically implausible for the Western Ghats landscape, so it has been identified as an error in the extraction process and must be re-extracted from the DEM. This means that the values and rankings for WS-6 are tentative. The relief ratio (Rh = R/Lb) ranged from 13.19m/km (WS-2) to 63.78m/km (WS-5), with 42.67m/km (WS-3). The ruggedness number (Rn = Dd × R/1000) ranges from 0.15 (WS-2) to 1.03 (WS-5) after recalculating using the corrected Dd value. It was found to be 0.91 (WS-3). The previous dissection index was the same as Rn x 1000 (Dd x R), so it was removed due to being redundant. The highest relief and ruggedness values are found in WS-5 and WS-3. This indicates the areas with the greatest variation in elevation and the steepest terrain. Such high relief can be a result of uplift and differential erosion of resistant rocks. It will not be interpreted as being caused by fault-controlled uplift.

Table 6: Relief Morphometric Parameters and Relief-Group Rank

Sub-Basin	Total relief, R (m)	Relief ratio, Rh (m/km)	Dd (km/km²)	Ruggedness number, Rn (= Dd × R/1000)	Relief-group rank
WS-1	567.34	27.003	0.51	0.290	4th
WS-2	273.59	13.185	0.54	0.147	5th
WS-3	1,589.37	42.668	0.57	0.913	2nd
WS-4	751.15	31.775	0.52	0.392	3rd
WS-5	1,763.62	63.784	0.58	1.030	1st
WS-6	1.00 (provisional; under re-extraction)	0.043	0.63	0.001	6th (provisional)

4.5. Integrated prioritisation

The integrated ranking includes all ten variables from the three groups of parameters (linear: Dd, Fs, Dt, ΣRb; areal: Rc, Re, Sf; relief: R, Rh, Rn) using an equally weighted composite method (see section 3.3, Table 7). WS-3 has the lowest composite score (CV = 2.0), meaning that it is ranked first, followed by WS-5 (2.8), WS-4 (3.7), WS-2 (3.8), WS-6 (4.2) and WS-1 (4.4). There is a large difference between the scores of WS-5 and the other sub-basins. However, there are only small differences in the CVs of WS-4, WS-2, WS-6 and WS-1. This means the sub-basins can be split into three groups: high priority (WS-3, WS-5), medium priority (WS-4, WS-2) and low priority (WS-6, WS-1). Within each group, there is no strong ordering. This ranking has been simplified to one process. It has also been corrected to remove any mention of a typographical error in the drainage density of WS-2, as it has now been recalculated.

Table 7: Parameter Ranks, Compound Value and Final Rank

Sub-basin	Dd	Fs	Dt	ΣRb	Rc	Re	Sf	R	Rh	Rn	CV	Rank
WS-1	6	4	5	5	2	5	5	4	4	4	4.4	6th
WS-2	4	1	2	3	5	4	4	5	5	5	3.8	4th
WS-3	3	2	3	1	1	2	2	2	2	2	2.0	1st
WS-4	5	6	6	6	3	1	1	3	3	3	3.7	3rd
WS-5	2	2	1	2	6	6	6	1	1	1	2.8	2nd
WS-6	1	5	4	4	4	3	3	6	6	6	4.2	5th

When removing each parameter individually, WS-3 was consistently ranked first and WS-5 second across all ten runs. WS-2 and WS-4 alternated between third and fourth place. WS-1 alternated between fifth and sixth place. WS-6 alternated between fourth and sixth place (Table 8). When generating 10,000 random weightings, WS-3 was ranked first in 86% of scenarios. WS-5 was ranked within the top two in 77% of scenarios. WS-1 and WS-6 were ranked in the bottom two in 81% and 64% of scenarios. WS-5 is dependent on the relief parameters. If the relief group is not included, WS-3 stays at the top, and WS-5 drops to fourth. Therefore, the top priority of WS-5 is due to the relief and ruggedness parameters. The rankings are therefore consistent at the top and bottom tiers, but not in the middle tier.

Table 8: Sensitivity of the Sub-Basin Ranking to Parameter Removal.

Sub-basin	Base rank	Leave-one-out rank range	Rank without relief group	% of weight sets ranked 1st	% ranked in top two	% ranked in lowest two
WS-1	6th	5–6	6th	0.0	0.4	81.0
WS-2	4th	3–4	2nd	0.0	2.3	25.0
WS-3	1st	1	1st	86.1	99.9	0.0
WS-4	3rd	3–4	5th	0.1	18.6	25.2
WS-5	2nd	2	4th	13.8	77.2	5.2
WS-6	5th	4–6	3rd	0.0	1.5	63.6

Table 9: Integrated Morphometric Prioritisation of Sub-Basins

Sl. No.	Rank	Sub-WS	Key morphometric indicators and priority tier
1	1st	WS-3	Highest priority – lowest compound values (2.0). Lowest Rc value (0.21) and highest Sf (4.15). Highest ΣRb (12.48) and ΣSLR (1.83). Highest relief (R 1,589 m) and ruggedness (Rn 0.91).
2	2nd	WS-5	Highest priority – highest relief (1,764 m), relief ratio (63.78 m/km) and ruggedness (Rn 1.03). Finest drainage texture (Dt 0.74). Highest Dd (0.58). Most compact shape (Rc 0.53). Rank would be fourth if relief factors were excluded.
3	3rd	WS-4	Medium priority – lowest Re (0.51) and FF (0.20). Highest Sf (4.97). Lowest Fs (0.169), Dt (0.30) and ΣRb (7.50). Moderate relief (751 m, Rn 0.39).
4	4th	WS-2	Medium priority – highest Fs (0.225). Dt 0.50. ΣRb 10.67. Irregular SLR (ΣSLR 1.44). Low relief (274 m), ruggedness (Rn 0.15).
5	5th	WS-6	Low priority (tentative) – highest Dd (0.63). Relief values based on unverified total relief of 1.00 m.
6	6th	WS-1	Low priority – lowest Dd (0.51). Compact shape (Re 0.67). Moderate relief (567 m, Rn 0.29). Highest third-order mean stream length (20.04 km).

4.6. Morphometric signatures, their possible tectonic significance and limitations in the Kabini River Basin

The morphometric results indicate a rigid dendritic drainage pattern with well-developed 1st order channels and a steep decrease in channel numbers with increasing order. WS-3 and WS-5 have high relief values and a high degree of ruggedness (Rn=0.91, 1.03) in combination with either a fine drainage pattern or elongate shape, making them the most structurally or tectonically influenced sub-basins if influence exists. WS-1 and WS-6 have the lowest signature, with WS-6 having a relief value that needs verification.

Dd, Fs, Dt, ΣRb and relief values will traditionally be interpreted as indicating a fractured landscape with higher degrees of dissection and uplift, whereas low values indicate increased stability. However, these signatures are also influenced by rainfall, lithology, permeability and erosional history. Irregular channel length ratios (WS-3, WS-2) may indicate faults/knickpoints but could also be lithological boundaries. This can be deciphered using longitudinal profile analysis, structural mapping and field verification. This can therefore be interpreted as a ranking of morphometric susceptibility. WS-3 and WS-5 are the first sub-basins to be investigated further using structural mapping, high-resolution lineament analysis, longitudinal profile and knickpoint analysis. The data provided do not justify undertaking seismic microzonation, fault detection or landslide hazard zonation, as this would require independent data from a seismological, geotechnical and inventory perspective.

4.7. Tectonic influence

Tectonic Influencing Parameters

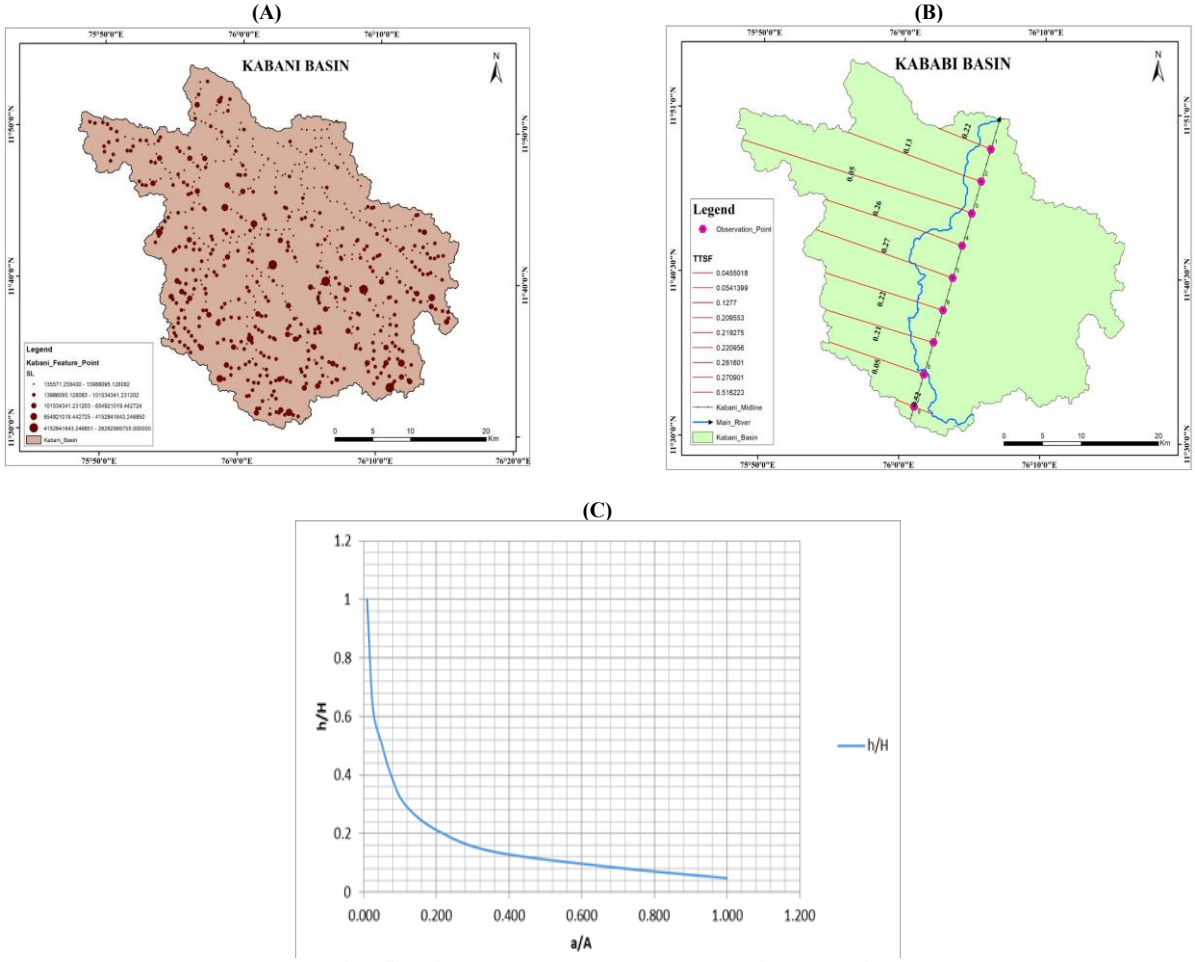


Fig. 3: Tectonic Influencing Parameters, SL (A), TTSF (B) and Hypsometric Curve (C).

4.7.1. StStream length gradient index

The SL map (Figure 3a) shows point values along the drainage system with an overall range of approximately 1.4 × 105 to 2.6 × 1010. This is several orders of magnitude greater than values found in the literature, so it indicates there was an error in the calculation or units. The text in the legend was also corrupted during export. As an accurate calculation and visualisation of the index was not possible, it has been omitted from the interpretation, abstract and prioritisation. The analysis has therefore not been concluded. A corrected analysis of the SL data using segmented values and anomaly classes will be carried out in future work.

4.7.2. Transverse topographic symmetry factor

The TTSF (Cox, 1994) was calculated using the ratio Da/Dd for 9 transects across the basin (Figure 3b). Da is the distance from the central line to the active meander belt (main stream), and Dd is the distance from the central line to the divide. For a perfectly symmetrical basin, TTSF = 0. As the stream migrates towards the divide, TTSF approaches 1. The values obtained for each of the transects were 0.05, 0.05, 0.13, 0.21, 0.22, 0.22, 0.26, 0.27 and 0.52. This gives an average TTSF of 0.21 (Table 10). Six of the 9 transects have a TTSF greater than 0.2. This indicates that the main stream has a moderate amount of lateral offset from the central line. The TTSF for the southernmost transect has a high value of 0.52. This is due to the short length of the transect and sensitivity to the central line and divide locations. Due to the fact that the transects were drawn along the main stem of the entire basin, we cannot attribute them to individual sub-basins. The previous statement that the TTSF > 0.2 only occurs in sub-basins WS-3 and WS-5 and that the baseline layer reaches a value of 1 is not supported by the data (max value of 0.52). Therefore, these statements have been removed. A moderate TTSF can be caused by tilting but can also be caused by lithological differences, structural controls on the trunk stream and inherent lateral migration of meandering streams.

4.7.3. Hypsometric curve

The overall basin hypsometric curve (Figure 3c) is highly convex. The curve shows a rapid decrease in h/H from 1 to around 0.3 for the first 10% of basin area, then more gradually down to around 0.05 at the basin outlet. The hypsometric integral calculated graphically can be seen to be around 0.2 (this value will be recalculated using the table of hypsometry from the DEM). This value is below the mature threshold of 0.35, indicating an old erosional stage. This is consistent with the classification by Strahler (1952). It has been incorrectly stated that a convex curve with a high hypsometric integral indicates a young neotectonic basin. This basin has a convex curve with a low hypsometric integral and indicates that most of the basin has been eroded down. Only a small proportion of the basin remains at high elevations. This suggests that the landscape has been eroding for a long period of time. Hypsometric curves were not plotted for the sub-basins. Therefore, the hypsometric integral was not used in the sub-basin ranking. The statements regarding HI values for WS-3, WS-5, and WS-6 have been removed.

4.7.4. Asymmetry factor

The index AF = 100 × (Ar/At) was calculated for the basin. This value can be calculated because the basin has a right bank of 605.17km2 and a left bank of 592.71 km2, meaning that it has a right bank percentage of AF = 50.52%. The difference from 50 is very minimal (|AF - 50| = 0.52%), meaning that the overall basin is almost symmetrical and there is no evidence of overall tilt (Hare & Gardner, 1985; Keller & Pinter, 2002). The previous statements about the basin being uplifted on the right-hand side and sub-basins having different AF values are not present because AF was not calculated for each sub-basin. The value is also well within the uncertainty of the basin boundaries produced using the DEM.

Table 10: Basin-Scale Tectonic Geomorphic Indices and Their Use in This Study

Index	Scale of computation	Result	Interpretation	Use in ranking
SL	Points along the drainage	$1.4 \times 10^5 – 2.6 \times 10^{10}$ (implausible)	Not interpretable (calculation or unit error)	Excluded
TTSF	Nine transects along the main stem	0.05–0.52; mean 0.21; six of nine > 0.2	Moderate asymmetry of the trunk stream; tilting not demonstrated	Not used
Hypsometric integral	Whole basin	≈ 0.2 (graphical estimate)	Mature-to-old erosional stage; no evidence of youthful uplift	Not used
AF	Whole basin	50.52% (605.17 / 592.71 km²)	Practically symmetric; no basin-wide tilt	Not used

Overall, the basin indices do not provide a clear indication. TTSF indicates that the trunk stream is moderately asymmetric. AF indicates that it is almost symmetrical. HI indicates that it is in a late-mature to old erosional stage. As SL could not be used, the indices do not indicate that the basin is experiencing active neotectonic deformation. They also do not allow sub-basins to be differentiated. The sub-basin order (Section 4.5) is based purely on morphometric values, and any tectonic interpretation would be a hypothesis that would need to be supported by structural, geophysical, seismic and field evidence.

5. Conclusion

A ranking system was developed using linear, areal and relief morphometric variables from CartoDEM. Equal weighting was applied to produce a repeatable composite ranking system. This system identified that WS-3 and WS-5 had the highest priority among the sub-basins. WS-3 had the lowest composite value (2.0) and ranked first in 86% of the 10,000 scenarios using random weighting. WS-5 ranked in the top two sub-basins (had the highest relief and ruggedness, Rn = 1.03, and the best drainage texture) in 77% of the scenarios. WS-2 and WS-4 were identified as having medium priority. WS-1 and WS-6 had the lowest priority. However, there was not a strong ranking within these groups. WS-5 ranked depending on the relief variables (without relief, WS-5 ranked fourth). WS-6 has yet to be verified for the relief value.

Tectonic indices at basin scale were not clear. The SL index was unreliable and was therefore omitted. The TTSF (0.05-0.52, average 0.21) indicates moderate trunk stream asymmetry. However, the asymmetry factor (50.52%) indicates near symmetry. The steeply concave

hypsometric curve and low integral (approx. 0.2) indicate that this is a mature erosional stage. This does not indicate active faulting, uplift, or neotectonic rejuvenation. This is due to the inability to separate lithological, climatic and erosional controls from tectonic controls.
Limitations include only using DEM-derived variables. No structural, seismic, geodetic, field or geochronological data were available. Tectonic indices were calculated at basin scale. The stream extraction threshold and DEM resolution will have an impact on the actual parameter values. This ranking is relative and depends on the chosen variables and weighting. This can be a problem when looking at medium-ranking sub-basins.
This ranking should be used as a screening tool. WS-3 and WS-5 should be the first sub-basins to be investigated in more detail. This includes structural mapping, lineament and longitudinal profile analysis, geophysics, and field verification. Recommendations cannot be made for seismic microzonation, active faulting, or landslide susceptibility zonation, as this cannot be determined from morphometric data alone. This may be used cautiously to help inform where geotechnical and groundwater investigations should be carried out.

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